DESIGN OF METAMATERIAL BASED ANTENNA USING UNIT CELLS

A

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUREMENTS FOR THE DEGREE

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IN

TELEMATICS AND SIGNAL PROCESSING

BY

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CERTIFICATE

*This is to certify that the thesis entitled, "DESIGN OF METAMATERIAL BASED ANTENNA USING UNIT CELLS" submitted by **Jyotisankar Kalia** in partial fulfilment of the requirements for the award of **Master of Technology** Degree in Electronics & Communication Engineering with specialization in **Telematics and Signal Processing** at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.*

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Date:

(Prof. S K Behera)
Supervisor

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CONTENTS

ABSTRACT

Metamaterials are artificial metallic structures having simultaneously negative permittivity (ε) and permeability (μ), which leads to negative refractive index. Due to negative index it supports backward waves i.e. inside Metamaterial phase velocities and group velocities are antiparallel. Metamaterial doesn't obey Snell's law, Doppler effect, Vavilov-Cerenkov radiation etc. No other material in the world shows the above properties like Metamaterial. Due to these unusual properties Metamaterial can change the electric and magnetic property of electromagnetic wave passing through it and because of these reasons when Metamaterial is used in the fabrication of microwave components and antennas the required properties can be enhanced. Also miniaturization in the size of the component is possible as the structural cell size of Metamaterial is less than one-fourth of the guided wavelength. Using this Metamaterial antenna the demerits of ordinary patch antenna like low gain and efficiency can be overcome and is useful in the field of wireless communication. The rationale behind the work is that small planar antennas are proposed using DNG (Double Negative) Metamaterials. The double negative property is being obtained by introducing unit cell structure. An unit cell consists of microstrip gaps and vias, whose behaviour is equivalent to the combination of series capacitors and shunt inductors respectively. The via leads to negative permittivity and microstrip gap leads to negative permeability. And this negative permittivity and permeability leads to negative refractive index due to this it exhibits unusual properties compared to readily available materials. Due to the unusual properties of the Metamaterials by using a single unit cell the antenna gives of 3.768 dB, overall efficiency of 53.76 and a VSWR of 1.6 at 5 GHz frequency which is very good for point to point wireless communication and wireless LANs. This antenna has better VSWR, gain and radiation efficiency compared to an ordinary patch antenna. And another Metamaterial antenna using three unit cells gives a better gain of 5.197 dB, overall efficiency of 92.5% and a return loss of -13.5 dB at 5 GHz frequency and the gain, efficiency and return loss are 4.183 dB, 60.78%, -14.5 respectively for 2.4 GHz. The results obtained through "CST MICROWAVE STUDIO" design software and are very good for wirelessly access network resources at home and elsewhere with up to 5 GHz performance, like IEEE 802.11a, widely available IEEE 802.11b, downwardly compatible IEEE 802.11g, and advanced IEEE 802.11n.

LIST OF FIGURES

CHAPTER 1

THESIS OVERWIEW

1.1 INTRODUCTION

In wireless Communination the antenna plays an important role. For point to point wireless communication and Wi-Fi the antenna should be compact and efficient for convenience. Metamaterial antennas are a class of antennas which use Metamaterials to increase performance like gain and efficiency of miniaturized (electrically small) antenna systems. Metamaterial is the only material (artificial) in the world which exhibits simultaneously negative permittivity and permeability which leads to negative refractive index. Due to having the negative refractive index it supports backward waves (antiparallel phase and group velocities) and does not obey some optical properties of nature. These special properties help Metamaterial to change the electric and magnetic property of electromagnetic waves passing through it and this helps in getting enhanced properties when applied to antenna design. Again as the structural average cell size of Metamaterial is less than one-fourth of the guided wavelength so it supports high degree of miniaturization. These Metamaterial antennas will be very suitable to use in WLAN (Both 2.4 and 5 GHz) because of its high performance and small size. Here Metamaterial antenna using unit cell is proposed, designed and simulated using CST Microwave Studio software.

1.2 LECTURE REVIEW AND METHODOLOGY

Metamaterial was developed in 1967 by Russian theorist Victor Veselago. In his paper, Veselago stated that although LH materials do not exist in nature, they can be artificially constructed. Veselago concluded that the realization of a LH Metamaterial will be possible with the discovery or construction of an isotropic negative μ material. Interest in Veselago's paper and LH materials begin to materialize when Professor Pendry at Imperial College demonstrated the first non-ferrite negative μ Metamaterial based on split ring resonators (SRRs) in 1998 Pendry's SRR was the cornerstone of the first bulk LH Metamaterial realization by a group at University of California, San Diego (UCSD) in 2000. So Metamaterial It's an artificial and only material having simultaneously negative permittivity and permeability. In 2003, the transmission approach by designing unit cell was proposed by Caloz, Oliner and Eleftheriades. After that research started on design of resonant antennas using Metamaterials. For Metamaterials the structural average cell size is less than one-fourth of the guided wavelength and because of this property high degree of miniaturization is possible in antenna design. In general Metamaterials can be realized using Split Ring

Resonators (SRRs) and thin wires but as these are not suitable for antenna application transmission line unit cells are used in antenna designing.

1.3 THESIS OUTLINE

CHAPTER 2:

This chapter contains introduction to Metamaterials, its history and developments, basic concept of Metamaterials i.e. unusual properties like simultaneously negative permittivity and permeability. The physical realization of Metamaterials is also focused here.

CHAPTER 3:

This chapter contains the overview of advantages of using Metamaterials in microwave passive components and filters. Also this chapter describes the use of Metamaterial in leaky wave antennas

CHAPTER 4:

This chapter describes the transmission line approach to realise Metamaterial for designing resonating antennas. The Metamaterial unit cell using via and microstrip gaps is focused here.

CHAPTER 5:

This chapter contains the design and simulation of DNG Metamaterial antennas using transmission line approach. The designed antennas are useful for wireless application like WLAN. The antennas are designed and simulated using CST Microwave Studio design software.

CHAPTER 6:

This chapter contains the conclusion of the work which describes that enhancement in antenna properties due to the unusual properties of Metmaterials and miniaturization due to the size of cell is less than one-fourth of the guided wavelength. Also this chapter lists the future work, references and publication.

CHAPTER 2

METAMATERIALS

2.1 INTRODUCTION

Metamaterials are recently developed artificial materials. It's the only material in the world having negative permittivity, negative permeability and negative refractive index simultaneously [1]. Due to having these three negative properties it exhibits unusual properties compared to readily available materials. In Greek Meta means above/after/beyond/superior, Metamaterials are named so as these exhibit properties beyond the properties of naturally available materials. It was developed in 1967 by Russian theorist Victor Veselago. These are artificial metallic structures that have dimensions much smaller than the wavelength of incident radiation. It gains its properties from structure rather than composition. It is counted as one of the, ten interesting futuristic material of the world due to its superior properties.

Metamaterial is not a special type of material, if an array of structures of any metal will be able to change the electric and magnetic property of the wave passing through it and leads to negative permittivity and refractive index simultaneously, that metallic structure can be called as metamaterial.

Metamaterials have sub-wavelength dimensions. Thus it renders high degree of miniaturization [5][14]. For Metamaterials, $p < \lambda g/4$

Where, P-Structural average cell size

λg -Guided wavelength

The paths of light and other electromagnetic waves can be controlled by materials. For example The lenses in eye glasses or microscopes, are nothing more than pieces of glass or plastic whose surfaces have been shaped in a particular way so as to achieve a desired optical function. Materials are used to form optical devices that operate across the electromagnetic spectrum, from radio waves to visible light.

Nature has provided us a rich palette of material properties from which to engineer useful optical devices. Yet, that palette is limited to Chemical synthesis, the conventional approach to material development, has so far not enabled us to access the entire range of material properties that should be theoretically possible. But chemistry is not the only process by which we can create materials. As an alternative approach, we can artificially structure a material by assembling a collection of objects together. These objects serve to replace the atoms and molecules of a conventional material, the result being a composite structure that can have electromagnetic properties unlike any naturally occurring or chemically synthesized material. Such composites have been termed Metamaterials, because they have properties that extend beyond materials found naturally.

Electromagnetic Metamaterials are artificially structured materials and are designed to interact with and control electromagnetic waves. Electromagnetic waves might be any type of wave in the electromagnetic spectrum (shown here on the figure below). Most of us are familiar with light waves in the visible spectrum, which occupy a small portion of the electromagnetic spectrum. Visible light waves have wavelengths from 400 to 700 nanometers (a nanometer is one-billionth of a meter), yet electromagnetic waves can have wavelengths of thousands of kilometers to trillionths of a meter.

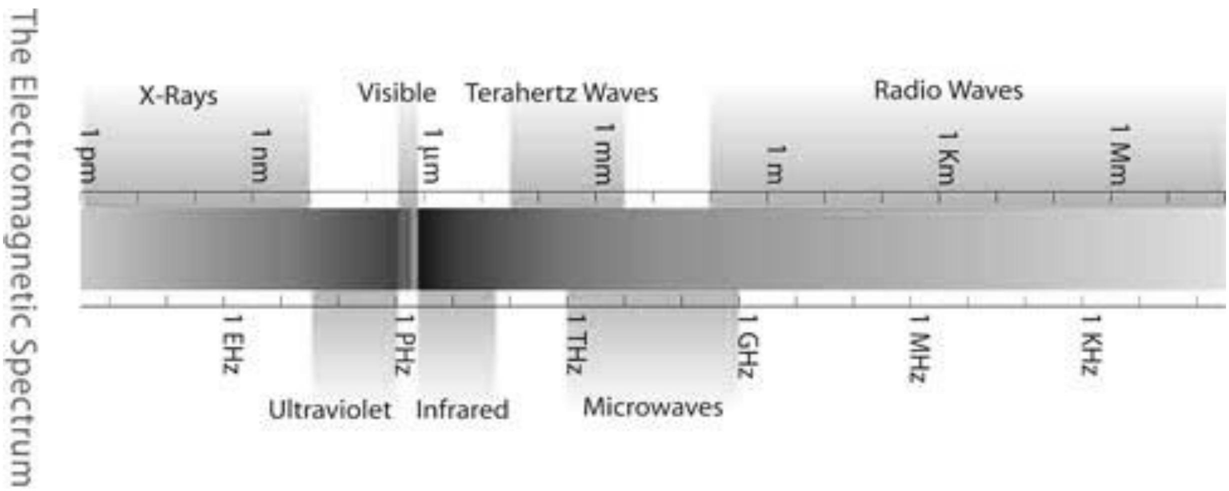


Fig 2.1: The EM Spectrum

When light (or electromagnetic) waves enter a material, the electric and magnetic fields of the wave cause electrons within the material to move around. This exchange of electromagnetic energy with the atoms and molecules of a material is the means by which materials can be used to control and manipulate light waves, forming the basis for electromagnetic devices.

The size and typical spacing of atoms within a material are on the order of angstroms, or tenths of one nanometer. That means that visible light waves, which are hundreds of nanometers in size, or longer wavelength waves cannot even come close to resolving the atomic structure. Although we know materials are formed from collections of atoms, we cannot see the individual atoms because the light we perceive is so much larger than the atomic scale. So, we are able to approximate the discrete atoms and molecules of a material as a continuous substance, whose properties derive not only from the individual atoms and molecules, but also their interactions.

We can easily come up with examples of optical devices, based on our experience with visible light. The lenses in telescopes, microscopes or eye glasses, are simply pieces of plastic or glass that take rays of light and cause them to converge or diverge. The properties of a lens are related to the material of which it is made, as well as its shape. Optical fibers and waveguides represent other classes of optical devices, in which the material is used to guide light from one point to another, like water passing through a pipe. Optical fibers are formed by 'pulling' carefully designed and optimized combinations of glasses, and are used to transmit light over surprisingly large distances.

The quality and diversity of optical devices is, at least in part, determined by the available range of electromagnetic properties of the materials used to make the devices. There are interesting opportunities here, because existing materials display only a subset of the electromagnetic properties that are theoretically available. Since we know that, ultimately, materials consist of atoms and molecules, it would seem reasonable to try to expand the available range of material properties by adjusting the composition of materials at the molecular level using chemistry. But there is another way to broaden our definition of a material. In effect, we can "fool" light by taking any arrangement of objects and assembling them into some sort of structure. If the size and spacing of the objects are much smaller than the wavelength of light, then the light will not be able to resolve the difference between our collection of objects and an actual material. What is the advantage? As it turns out, material properties obtained by engineering the geometry of macroscopic objects can extend well beyond what is obtainable by chemical synthesis. Consequently, a structured material is now often referred to as a Metamaterial, since its electromagnetic properties are often beyond those of any known naturally occurring materials.

The Metamaterials concept allows us to avoid the techniques of chemical synthesis, and arrive at new electromagnetic materials by changing the geometry of other objects. We no longer need to think about reaction dynamics, but rather how to design the geometry of Metamaterial elements so that a composite formed from these elements will have desired properties.

2.2 PROGRESS ON METAMATERIALS

1967- Theoretically proposed by Vesalogo

1999- First negative Mu material by Pendry

2000- First Metamaterial by Smith

2003- Transmission approach by Caloz, Oliner, Eleftheriades

2005-New structures

2009-Miniaturized structures for optical frequencies

2.3 MAJOR APPLICATION AREAS OF METAMATERIALS

- Microwave Invisibility Cloaks
- Invisible Submarines
- Revolutionary Electronics
- Negative Refractive-Index Lenses
- Waveguides and Microwave Components
- Compact and Efficient Antennas

2.4 THEORETICAL SPECULATION BY VIKTOR VESELAGO

The history of Metamaterials started in 1967 with the visionary speculation on the existence of "substances with simultaneously negative values of e and μ" [1] (fourth quadrant of ὲ- μ space by the Russian physicist Viktor Veselago. In his paper, Veselago called these "substances" left-handed (LH) to express the fact that they would allow the propagation of electromagnetic waves with the electric field, the magnetic field, and the phase constant vectors building a left-handed triad, compared with conventional materials where this triad is known to be right-handed. Several fundamental phenomena [10] occurring in or in association with LH media were predicted by Veselago:

1. Necessary frequency dispersion of the constitutive parameters

2. Reversal of Doppler effect

3. Reversal of Vavilov-Cerenkov radiation

4. Reversal of the boundary conditions relating the normal components of theelectric and magnetic fields at the interface between a conventional/right-handed (RH) medium and a LH medium

5. Reversal of Snell's law

6. Subsequent negative refraction at the interface between a RH medium and an LH medium

7. Transformation of a point source into a point image by a LH slab

8. Interchange of convergence and divergence effects in convex and concave lenses, respectively, when the lens is made LH

9. Plasmonic expressions of the constitutive parameters in resonant-type LH

2.5 THE LEFT HANDED METAMATERIALS

Electromagnetic Metamaterials are effectively homogenous artificial structures [3] engineered to provide electromagnetic properties not readily observable in nature. Effectively homogeneous means that scattering/diffraction is a minor/non-existent effect in a propagating wave in a Metamaterial. Lattice constants of the Metamaterial are much smaller than the electromagnetic wave. So what kind of unique electromagnetic properties can Metamaterials provide? First let's define what we mean by electromagnetic properties. Electromagnetic properties are the effect a material has on the electric and magnetic field of a wave, which is determined by the material's permittivity and permeability respectively. The four possible combinations of permittivity and permeability are shown in fig. 2.1.

As shown in the figure, when the wave incident from air to plasmas and ferrites it gets reflected so the wave attenuates. But in case of conventional materials and Metamaterials positive and negative refraction takes place respectively and wave propagates [16]. Materials that reside in quadrant I, II and III are known to exist in nature, however naturally occurring materials with negative permittivity and negative permeability have not yet discovered. In 1967 Victor Veselago speculated about the existence of such double negative materials in his paper entitled "The electrodynamics of substances with simultaneously negative permittivity and negative permeability". Veselago discussed the unique phenomena occurring for an electromagnetic wave in a double negative material. These are

1. Electric field, Magnetic field and Wave vector form a left-handed.(LH) triad

2. Negative refractive-index leads to reversal of Snell's law, Doppler Effect and Vavilov Cerenkov Radiation

3. Frequency dispersion

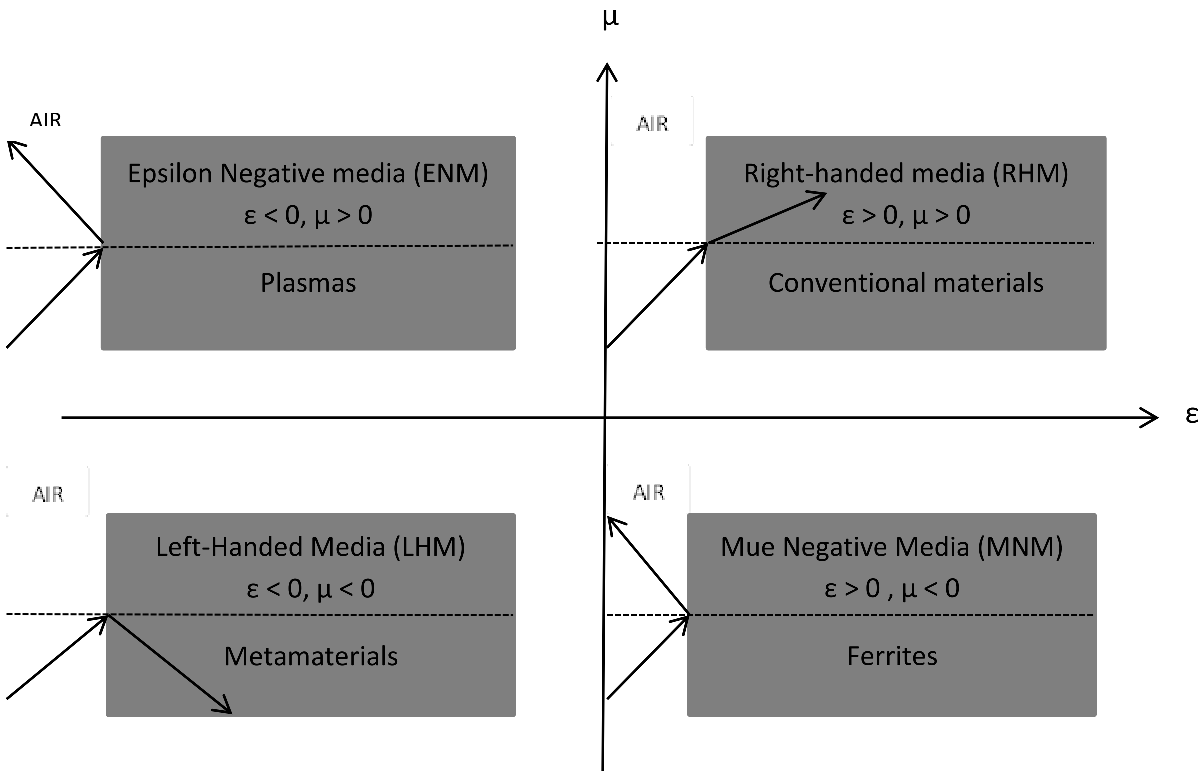


Fig 2.2: ε-μ Space

2.6 BACKWARD WAVES

Since the electromagnetic wave in a double negative material forms a LH triad, double negative materials are generally referred to as LH materials. The LH triad means that power flows away from the source (group velocity is positive) while the phase front travels towards the source (phase velocity is negative) [15]. Therefore LH materials support backward wave i.e. wave with antiparallel group and phase velocities. This backward wave phenomenon can be observed in Fig.2.2 which shows the electric field magnitude plot of an air-filled rectangular waveguide with its middle section filled with a fictional LH material of ε = -1 and μ = -1.

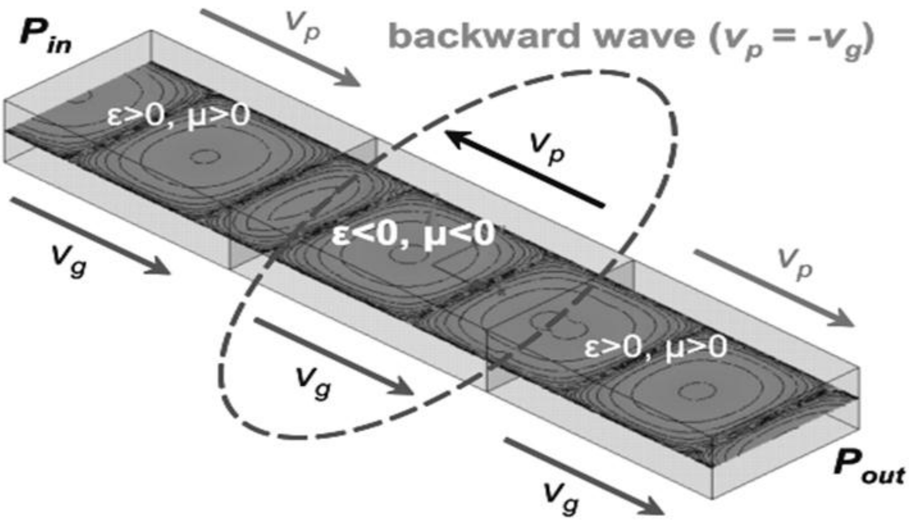


Fig 2.3: Antiparallel Phase and Group Velocity if Waveguide Made of Metamaterial

2.7 NEGATIVE REFRACTIVE INDEX

Metamaterials are artificial material which exhibit negative permittivity, negative permeability and refractive index, [17] which is not found in readily available materials. Metamaterials have negative refractive index that is a reversal of Snell's law, hence called as negative index materials. Due to negative refractive index, the group and phase velocities of electromagnetic wave appear in opposite direction such that the direction of propagation is reversed with respect to the energy flow direction. Negative μ_r and ε_r occur in nature, but not simultaneously [19]. Negative refraction can be achieved when both μ_r and ε_r are negative, as described in the following equation.

$$
\begin{aligned}
n &= \sqrt{(-\varepsilon_r)(-\mu_r)} \\
&= \sqrt{\varepsilon_r (e^{-j\pi}) \mu_r (e^{-j\pi})} \\
&= \sqrt{\varepsilon_r \mu_r} (e^{-j\pi})^{1/2} (e^{-j\pi})^{1/2} \\
&= \sqrt{\varepsilon_r \mu_r} (e^{-j\pi/2} e^{-j\pi/2}) \\
&= -1\sqrt{\varepsilon_r \mu_r} < 0 \text{.........}(i)
\end{aligned}
$$

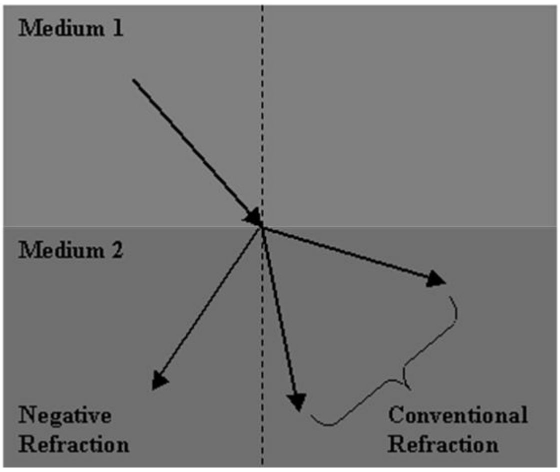
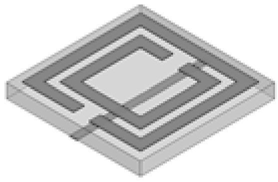


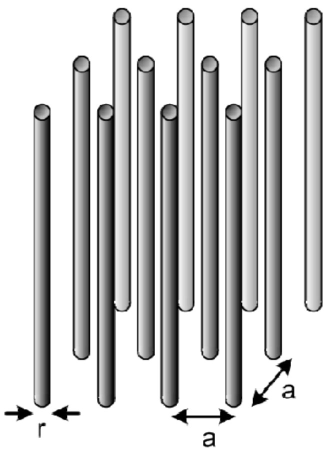
Fig 2.4: Normal and Negative Refraction

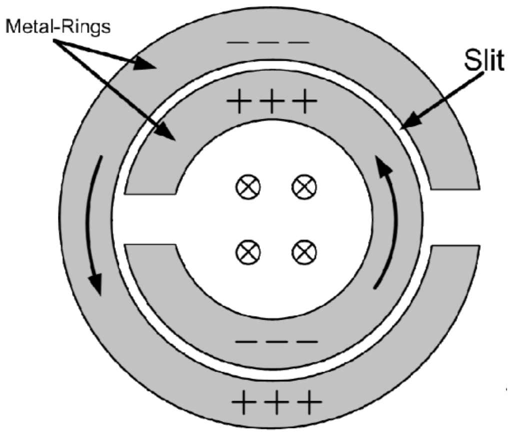
2.8 HOW ARE LH MATERIALS ARE REALIZED?

Early metamaterials relied on a combination of Split-ring resonators (SSRs) and conducting wires/posts. SSRs used to generate desired relative permeability, μ_r for a resonant band of frequencies [7]. Conducting posts are polarized by the electric field, generating the desired relative permittivity, ε_r for all frequencies below a certain cut-off frequency. As shown in fig. 4(a) all thin wires have same radius ‘r’ and are separated by a distance ‘a’ from each other.



(a) SRR and Metal Wire (b) Array of SRRs and Wires to form Metamaterial





(c) Thin Wires (d) Slit and Ring in a Circular SRR

Fig. 2.5: SRR and Thin Wire

2.9 VESELAGO AND NEGATIVE INDEX

All transparent or translucent materials that we know of possess positive refractive index i.e. a refractive index that is greater than zero. However, is there any fundamental reason that there should not be materials with negative refractive index? This question was asked by Victor Veselago, a Russian physicist. In 1968, Veselago published a theoretical analysis of the electromagnetic properties of materials with negative permittivity and negative permeability. The electric permittivity and the magnetic permeability are commonly used material parameters that describe how materials polarize in the presence of electric and magnetic fields. Maxwell's equations relate the permittivity and the permeability to the refractive index as follows:

The sign of the index is usually taken as positive. However, Veselago showed that if a medium has both negative permittivity and negative permeability, this convention must be reversed: we must choose the negative sign of the square root!

This reversal of the refractive index can seem confusing. As an example, it is often said that the velocity of a wave in a material is given by ‘c/n’, where ‘c’ is the speed of light in vacuum and ‘n’ is the refractive index. The implication of a negative index, then, is that the wave travels backwards

When the refractive index is negative, the speed of the wave given by ‘c/n’ is negative and the wave travels backwards toward the source [3] .Yet, we would reasonably expect that since energy is incident on the material from the left, the energy in the the material should likewise travel to the right, away from the interface. The definition ‘c/n’ is well known as the phase velocity and determines the rate at which the peaks (or zeros) of a wave pass a given point in time. But this is not most relevant definition of a wave's velocity, we can also define the group, energy, signal and front velocities, and these generally differ from the phase velocity.

When the refractive index of a material does not vary with the wavelength of light that travels through it, then all of the velocity definitions above are the same and we can intuitively use the index as a measure of the wave's velocity. However, when a material is dispersive, has an index that varies with wavelength, then the various definitions of velocity no longer agree and we can no longer determine the actual velocity of the wave, or at least the rate at which energy is transported, from the value of the refractive index alone. So, even though the positive and negative index materials in the figure above seem to display drastically different behaviours, a calculation of the group or the energy velocity reveals that energy is actually flowing to the right in both cases. Thus, as Veselago showed, the phase and energy velocities are opposite in a negative index material.

2.10 NEGATIVE REFRACTION LEADS TO REVERSAL OF SNELL'S LAW

One of the most fundamental of optical effects is refraction, or the bending of light as it crosses the interface between two materials. The phenomenon of refraction is well-known to most of us. For example, an object under water viewed by an observer in air always appears closer to the surface than it actually is. Refraction is the basic principle behind lenses and other optical elements that focus, steer, guide or otherwise manipulate light. Highly sophisticated and complex optical devices are developed by carefully shaping materials so that light is refracted in desired ways (think of a camera lens or a microscope objective).

The underlying principle of refraction can be easily understood and applies to all electromagnetic waves, not just visible light. Every material, including air, has an index of refraction (or refractive index). When an electromagnetic wave traverses the interface from a material with refractive index n1 to another material with refractive index n2, the change in its trajectory can be determined from the ratio of refractive indices n2/n1 by the use of Snell's Law [10].

To apply Snell's Law, consider an interface between two materials and an imaginary line that runs perpendicular to the interface (the surface normal). The angles in Snell's law are measured away from the surface normal. If the refractive indices of the two materials are not equal, the angle of the transmitted beam will differ from the angle of the incident beam. The beam is then bent at the interface.

A common way to determine the refractive index of a material is to form a prism out of the material, shine a beam of light through it and observe the deflection of the beam on the other side. Light enters the prism through one of the interfaces at direct incidence, striking the opposite interface at an oblique angle. The figure below shows what happens to the beam when the material has the same index as the surrounding medium, or has an index that is greater than the surrounding medium but either positive or negative.

CHAPTER 3

METAMATERIALS IN MICROWAVE COMPONENTS, FILTERS AND ANTENNAS

3.1 INTRODUCTION

Metamaterials can be used in designing of microwave passive components [6], filters and antennas for miniaturization and to get enhanced properties [8]. The unusual properties of Metamaterials such as negative permittivity, permeability and refractive index and supporting backward waves plays important role to get the properties [12]. Some microwave passive components and the leaky wave antenna using Metamaterials is discussed in this chapter

3.2 MICROWAVE PASSIVE COMPONENTS AND FILTER USING METAMATERIALS

3.2.1 Single Band Microstrip Branch Line Coupler

A single band microstrip branch line coupler using Metamaterial is shown in fig 3.1(a). The main advantages of this coupler are

- Power splits equally between the through and coupled ports.
- -900 and -1800 phase shift between through and coupled port respectively, with reference to the input port.

3.2.2 Phase Agility using Metamaterial Structure

A phase agitator using Metamaterial structure is shown in fig. 3.1(b). The structure consists of microstrip lines for the high-impedance branches and NRI (Negative Refractive Index) lines for the low impedance branches which composed of series capacitor and parallel inductor.

The main advantages are

- Power splits equally between the two output ports.
- Zero phase shifts between input and coupled port.
- Positive phase quadrature (900) at through port with respect to input port.

3.2.3 Microstrip Backward Coupler (Coupled Line)

A microstrip backward coupler using Metamaterial is shown in fig. 3.1(c).The main advantages are

- Power is coupled backward (from input port 1 towards port 2) unlike in forward couple (port1 towards port 3/4).
- Backward propagation of power is achieved by placing CSRR (Complementary Split Ring Resonators) at ground plane and the upper microstrip line replaced by series capacitor.

3.2.4 Dual Band Branch Line Coupler

The dual band branch line coupler using Metamaterial structure is shown in fig. 3.1(d). The main advantage is

- Dual band with high impedance matching characteristics

3.2.5 Asymmetric Backward wave Directional Coupler

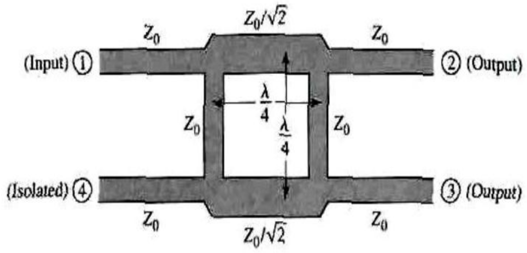
An asymmetric backward wave directional coupler using Metamaterial structure is shown in fig. 3.1(e). Its main advantages are

- High directivity over 40 dB and high isolation over 70 dB
- Broadband and tight coupling characteristics

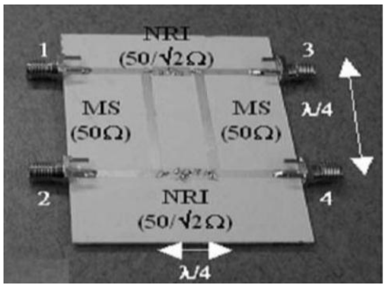
3.2.6 CPW Band Stop Filters with SRRs

A CPW band stop filters with Split Ring Resonators is shown in fig. 3.1(f). Its main advantage is

1. High impedance matching

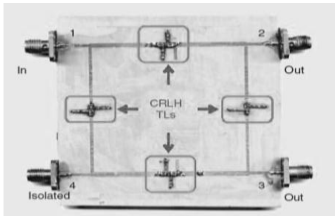


(a) Single Band Branch Line Coupler

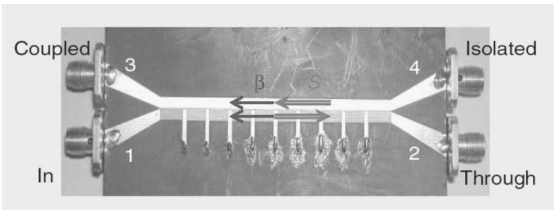


(b) Phase agitator using metamaterial

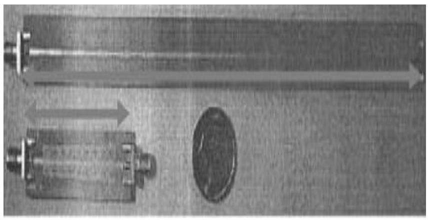
(c) Microstrip Backward Coupler



(d) Dual Band Branch Line Coupler



(e) Asymmetric Backward wave Directional Coupler



(f) CPW Band Stop Filters

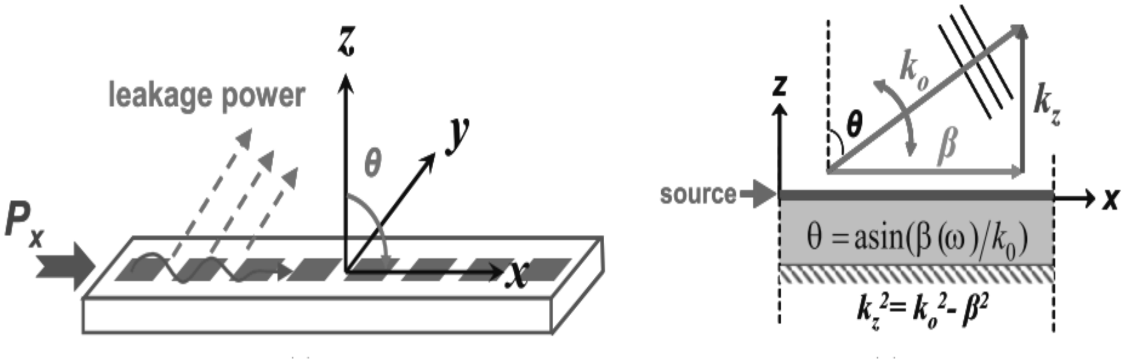
Fig 3.1 Metamaterial Microwave Components and Filters

3.3 DOMINANT MODE LEAKY WAVE ANTENNA

The CRLH Metamaterial transmission line can be used as a leaky-wave antenna when operated in the fast-wave region. In particular, a balanced CRLH unit-cell based on microstrip technology is designed, dispersion and blotch impedance diagrams are used to confirm the balanced condition, which is required for continuous beam scanning.

3.3.1 Introduction

Leaky-wave antennas [15] are a form of traveling wave antennas whose electromagnetic field is excited by a wave incident in the interior of the guiding structure. As this wave propagates down the guiding structure, some of its energy leaks out, this leakage power translate to far-field radiation [13]. Any leftover guided energy is simply lost to a matched load at the other end of the leaky-wave antenna. The general model of a leaky-wave antenna is shown in fig. 3.2 (a).



(a) Concept (b) Principle of Operation

Fig 3.2: Leaky Wave Antenna

Figure 3.2 (b) shows that by changing the frequency, the propagation constant of the travelling wave changes and the radiated beam is scanned. θ is the Scan Angle of the resulting radiation measured from broadside. However, conventional leaky-wave antennas require complex feeds to excite a higher-order mode for radiation, since in order for leakage to occur has to be real. A CRLH transmission line can be used as a dominant-mode leaky-wave antenna capable of both backfire [18].

Fig 3.3: Completed Leaky Wave Antenna with Feed Sections

3.3.2 One Dimensional CRLH Unit Cell

The CRLH unit-cell used for realizing the leaky-wave antenna is shown in fig. 3.4. This unit-cell is based on microstrip technology. The LH series capacitance (C) is provided by the interdigital capacitor, while the LH shunt inductance (L) is provided by the shorted stub. The RH series inductance (L) and shunt capacitance (C) are provided by the current and voltage gradient across the interdigital capacitor, respectively.

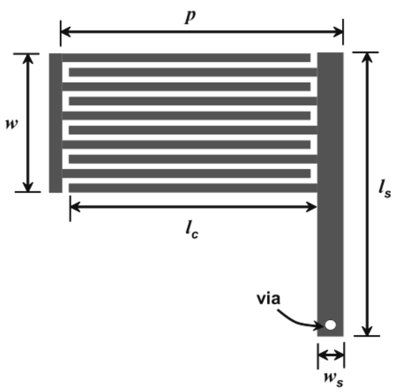


Fig 3.4: One Dimensional CRLH Unit Cell

The CRLH unit-cell of Fig. 3.4 is suited for applications that require a balanced unit-cell due to the following reasons:

- Ability to achieve large or small values of series capacitance by adjusting interdigital capacitor (i.e. number of finger pairs, width/length of fingers and spacing between fingers)
- Shunt inductance can also be varied over a wide range.

However, some of the drawbacks of the interdigital capacitor-based unit-cell are:

- Self-resonance of the interdigital capacitor can occur within the desired CRLH operational pass-band, bonding wires can be used to eliminate these resonances
- Small gap size between interdigital fingers is best suited to planar electromagnetic (EM) simulation.
- Radiation occurs in the fast-wave region, which may not be desired for non-radioactive applications, shielding can be used.

CHAPTER 4

THE TRANSMISSION LINE APPROACH

4.1 HOW ARE LEFT-HANDED METAMATERIALS REALIZED?

In his paper [1], Veselago also stated that although LH materials do not exist in nature, they can be artificially constructed. In particular, Veselago concluded that the realization of a LH Metamaterial will be possible with the discovery or construction of an isotropic negative μ material. When Veselago published his paper, materials with $\mu < 0$ were not known to exist. For 30 years, Veselago's paper and its theory was not investigated any further. Interest in Veselago's paper and LH materials begin to materialize when Professor Pendry at Imperial College demonstrated the first non-ferrite negative μ Metamaterial based on split ring resonators (SRRs) in 1998 Pendry's SRR was the cornerstone of the first bulk LH Metamaterial realization by a group at University of California, San Diego (UCSD) in 2000 . The UCSD's LH Metamaterial was based on combining a SRR (negative μ) with a metal wire (negative ε)

4.2 WHY TRANSMISSION LINE APPROACH?

The SRR based LH Metamaterials only exhibit LH properties around the resonance of the SRR. Therefore realiazation of LH Metamaterials using SRRs are known as the resonant approach [11]. In terms of microwave engineering applications, the resonant approach towards LH Metamaterial is not practical for the following reasons

- Bulky, not applicable to planar microwave circuits
- Narrow-band due to requirement of operation near SRR resonance
- Lossy due to requirement of operation near SRR resonance

To overcome the drawbacks of SRR based LH Metamaterials for microwave engineering applications researchers realized that backward wave transmission line can be used to realize non resonant LH Metamaterials. This transmission line approach towards LH Metamaterials is based on the dual configuration of a RH/conventional transmission line. As shown in the figure conventional transmission lines are modelled as unit cells with series inductance (LR) and shunt capacitance (CR), while LH transmission lines are modelled as unit cells with series capacitance (CL) and shunt inductance (LL)

(a) RH Transmission Line Unit Cell (b) LH Transmission Line unit Cell

Fig 4.1: Transmission Line Circuit Model Unit Cell

The propagation constant for the RH and LH unit cell are given by equation (i) and (ii) respectively

$$\beta_{RH} = \omega\sqrt{C_R L_R}\,........(i)$$

$$\beta_{LH} = \frac{1}{\omega\sqrt{C_L L_L}}\,........(ii)$$

By plotting a ω-β diagram, commonly referred to as dispersion diagram, the group velocity (v_g=dω/dβ) and phase velocity (v_p=ω/β) of a material can be directly observed. The dispersion diagram [15] for the unit cell are plotted in fig. 4.2

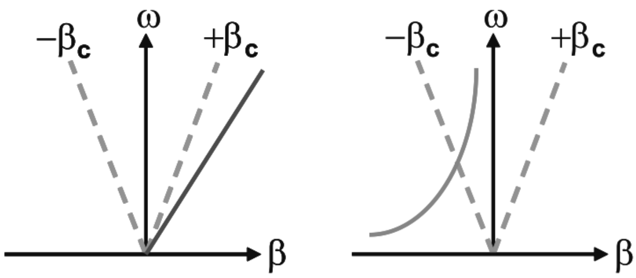


Fig 4.2: Dispersion Diagram of Unit Cell

The dispersion diagrams of fig. 4.2 shows that vg and v_p of the RH transmission line are parallel ($v_g v_p$>0), while v_g and v_p for LH transmission line are antiparallel ($v_g v_p$<0). Therefore a RH transmission line supports a forward wave, while a LH transmission line supports a backward wave. In addition, the LH transmission line's dispersion diagram shows that vg approaches g infinity as increases. However, this is not physically possible since it violates Einstein's special theory of relatively. This means that a pure LH transmission line is not possible. Instead, the unit-cell model has to be modified to account for unavoidable parasitic effects with any practical realization of a LH transmission line.

4.3 COMPOSITE RIGHT/LEFT-HANDED (CRLH) TRANSMISSION LINE

A pure LH transmission line [20] cannot be physically realized due to RH parasitic effects. As a result, a LH transmission line is a more general model of a composite right/left-handed (CRLH) transmission line, which also includes RH attributes. The general model of a CRLH TL is shown in Fig. 4.3 and consists of a series RH inductance LR, a series LH capacitance CL, a shunt RH capacitance CR , and a shunt inductance LL. A pure LH transmission line cannot be physically realized due to RH parasitic effects. The propagation constant for the CRLH unit-cell is given by

$$\beta_{CRLH} = S(\omega)\sqrt{\omega^2 L_R C_R + \frac{1}{\omega^2 L_L C_L} - \left(\frac{L_R}{L_L} + \frac{C_R}{C_L}\right)} \text{..........}(iii)$$

Where

$$S(\omega) = -1 \quad if \quad \omega < \omega\Gamma 1 = \min\left(\frac{1}{\sqrt{L_R C_R}}, \frac{1}{\sqrt{L_L C_R}}\right)$$

$$S(\omega) = +1 \quad if \quad \omega > \omega\Gamma 2 = \max\left(\frac{1}{\sqrt{L_R C_L}}, \frac{1}{\sqrt{L_L C_R}}\right)$$

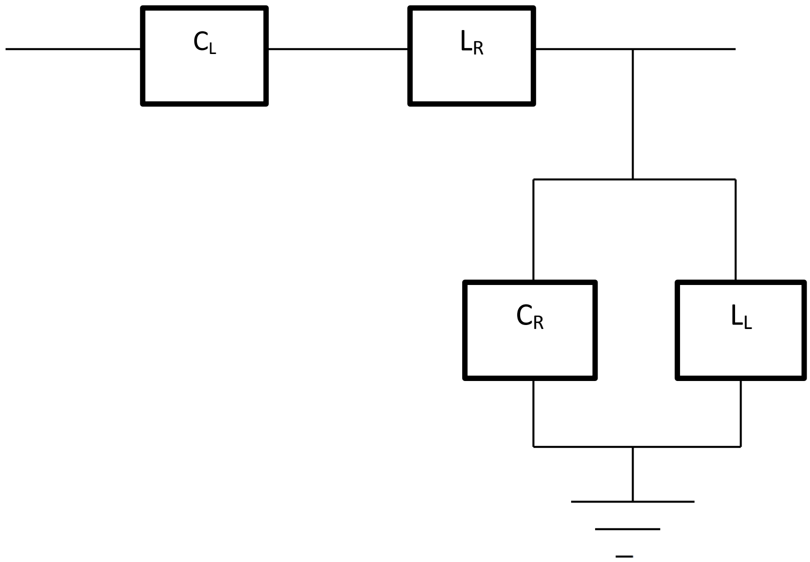
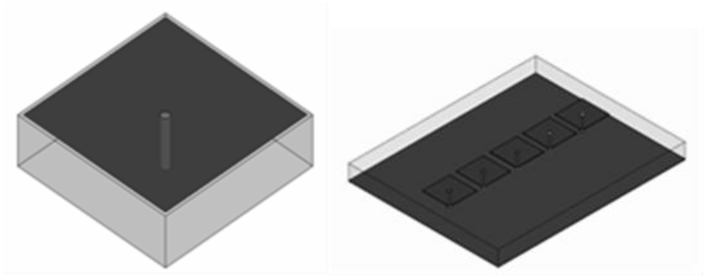


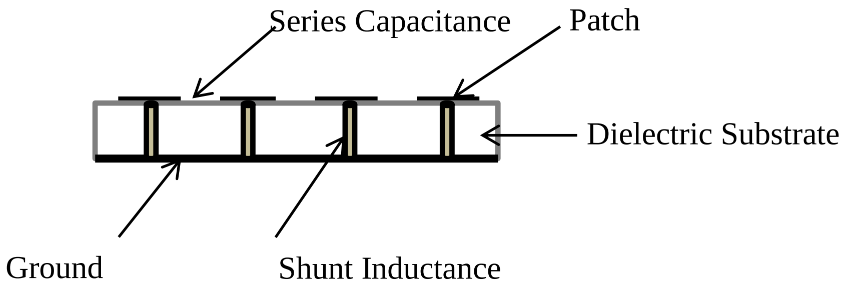
Fig 4.3: General Model of CRLH Transmission Line

4.3.1 The Transmission Line Approach CRLH Unit Cell

A CRLH unit cell [15] is a combination of via (cylindrical metal generally perfect electric conductor) and microstrip gaps whose behavior is equivalent to the combination of series capacitors and shunt inductors respectively. And is used to realize Metamaterial and this is called transmission line approach to realize Metamaterial. Metamaterial using unit cell is called transmission line approach. The transmission line approach is made by shunt inductance and series capacitance. The via is used to shot the ground plane and the patch and behaves like a shunt inductor and the series capacitors can be obtained by the gaps created by the free plates or patches.



(a)Via in an Unit Cell (b) Cascaded Unit Cell



(c) Side View of the Cascaded Unit Cells

Fig 4.4: CRLH Unit Cell Structure

CHAPTER 5

METAMATERIAL BASED ANTENNAS FOR WIRELESS APPLICATIONS

5.1 COMPACT HIGH RADIATION METAMATERIAL ANTENNA FOR WIRELESS APPLICATION

This antenna is designed using a single unit cell and suitable for wireless application at GHz frequency.

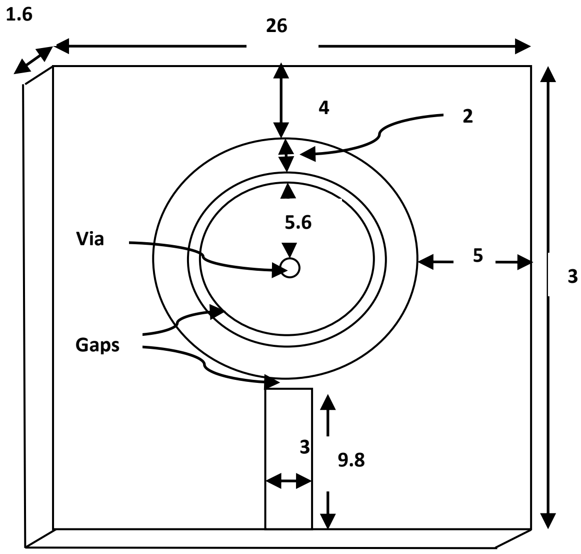
5.1.1 INTRODUCTION

The utilization of the unusual properties of the Metamaterials [1] in small antennas is tried here to get an efficient antenna. Metamaterials were introduced by Veselago [3] in 1967. Metamaterials are human made artificial materials which exhibit negative permittivity, negative permeability and negative refractive index, not found in readily available materials. For the proposed antenna only the negative permittivity and permeability are important. Veselago first analyzed theoretically the wave propagation in a material with a negative magnetic Permeability and a negative electric permittivity [4]. In such a left-handed (LH) material [15], the electric field, the magnetic field, and the wave vector of an electromagnetic wave propagating obey the left-hand rule (instead of the right-hand rule for usual materials). In Greek Meta means above/after/beyond/superior. So Metamaterial is named so as it exhibits properties beyond the properties of naturally available materials. For Metamaterials the structural average cell size is smaller than the guided wavelength. It gains its properties from structure rather than composition and is a combination of metal and dielectric composite. The advantage of using Metamaterial structures in patch antennas is that enhanced antenna properties can be obtained as well as size of the antenna can be reduced for convenience. For the proposed antenna a cylindrical via is used throughout the whole antenna width, which is the main radiating element of the antenna [2].

5.1.2 DESIGN OF THE DNG ANTENNA

Here we have designed a single layer planar DNG [4] antenna photo etched on thin substrate [2]. First we have taken a ground plane of 0.4mm next a rectangular substrate (26mm×30mm×1.6mm) of duroid having permittivity 2.2 is developed. A circular patch having radius 8mm, thickness 0.1mm and a gap circle having outer radius 6mm and inner radius 5.8mm is printed on the substrate. As shown in the fig. 5.1 at the centre point of the patch, a via of radius 0.2mm is inserted. For feeding we have used a microstripline of length 9.8mm, width 3mm and thickness 0.1mm, by using the above dimensions a gap of 0.2 mm is found between the microstrip line and the patch. Our antenna is simulated using CST

Microwave Studio [25] based on finite integration method. But as CST transient solver doesn't support negative permittivity and permeability we can't enter negative permittivity and permeability values for the Metamaterial directly, so we have used a via (inductive), a circlular gap in the patch (conductive) and a gap of 0.2mm between the patch and the microstripline (capacitive) to directly convert the PEC (Perfect Electric Conductor) patch to DNG Metamaterial [2]. Directly, negative permittivity and permeability values can be entered using HFSS, based on finite element method.



Via Radius=Patch Gap=0.2
All Dimensions in mm

Fig 5.1: Structure of the Proposed Antenna

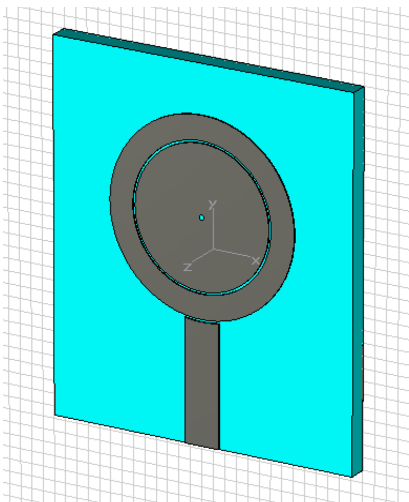


Fig 5.2: Prospective View of the Antenna

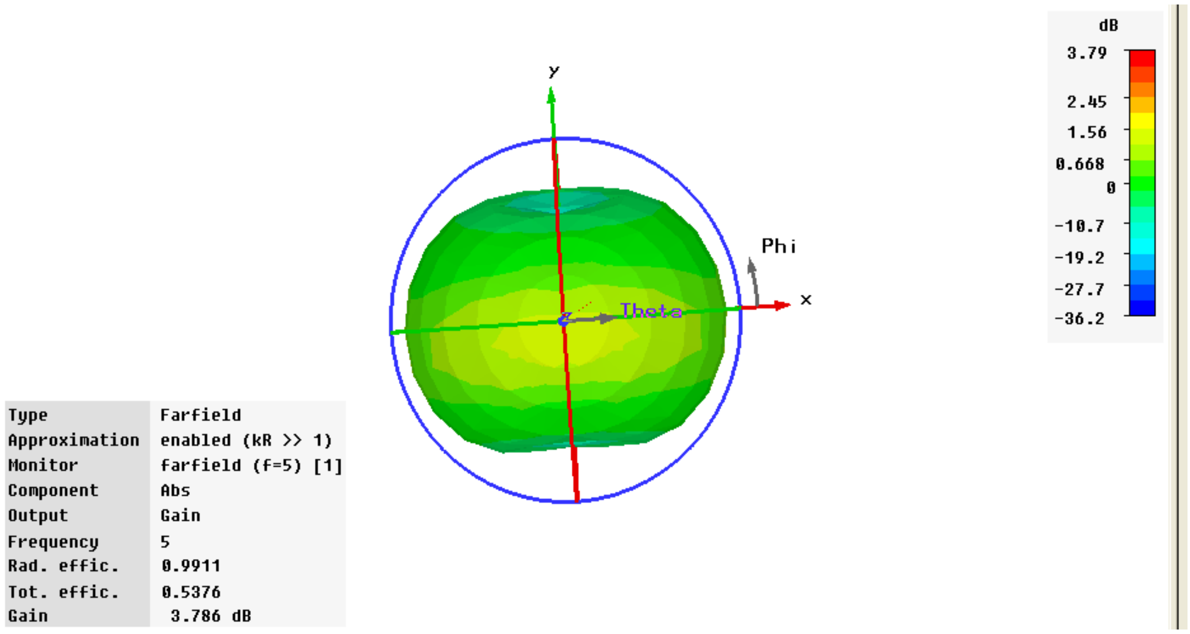


Fig 5.3: 3D Radiation Pattern at 5 GHz

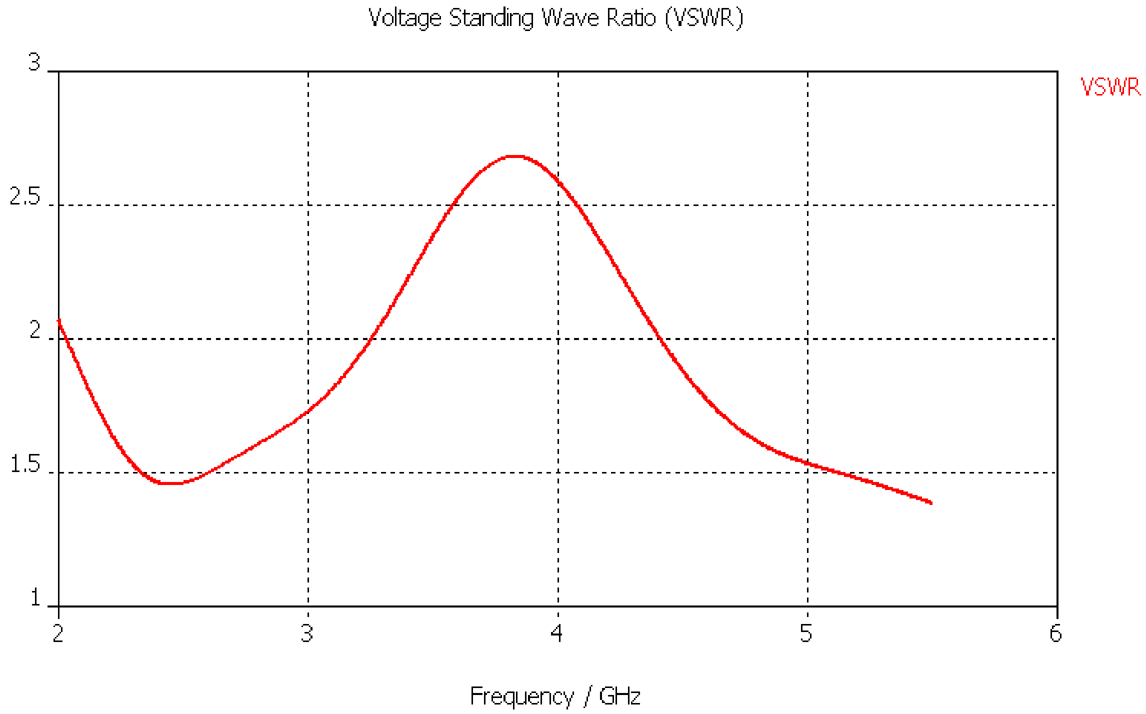


Fig 5.4: VSWR Curve

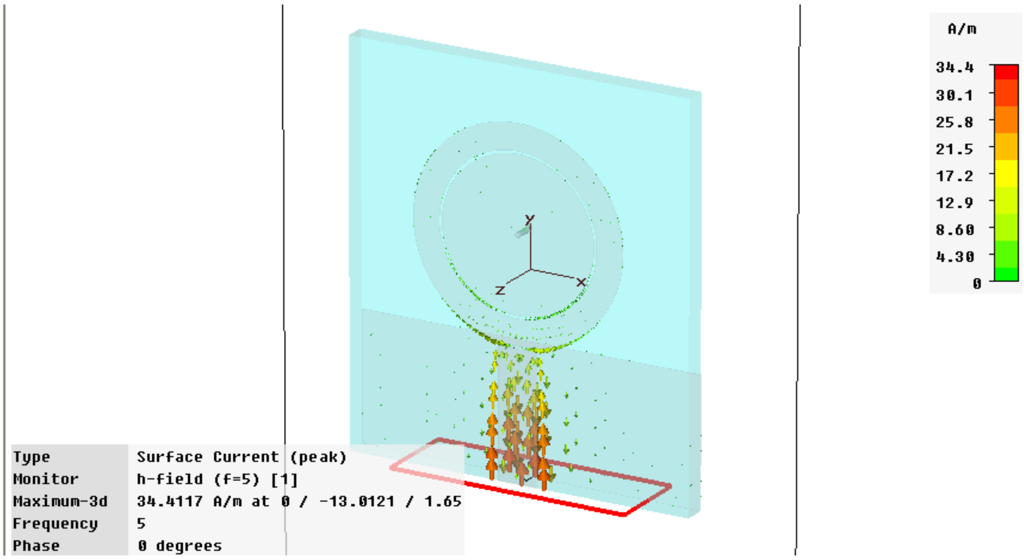


Fig 5.5: Surface currents at 5 GHz

Fig. 5.6: Prototype of Fabricated Patch

5.1.3 RESULTS AND DISCUSSION

For simulation of our antenna we have taken the frequency range 2.4-5.5 GHz to satisfy the wireless requirements [21]. From the 3D radiation pattern shown in fig 5.3, at 5 GHz frequency the gain of the antenna is 3.768 dB, which is enough for point to point wireless communication [24]. The radiation efficiency for our antenna is excellent i.e. 99.11%. As shown in fig 5.4 the VSWR at 5 GHz is 1.6. Fig 5 shows a well-balanced surface current at 5 GHz.

The experimental verification of fabricated patch could not be carried out due to unavailability of high range of network analyser in our lab.

5.2 METAMATERIAL UNIT CELL ANTENNA FOR WLAN APPLICATION

This antenna is designed using three unit cells and suitable for WLAN application at 2.4 and 5 GHz frequencies.

5.2.1 INTRODUCTION

The utilization of the unusual properties of the Metamaterials [1] in small antennas is tried here to get an efficient antenna. Metamaterials were introduced by Veselago [3] in 1967. Metamaterials are human made materials. In Greek Meta means above/after/beyond/superior, so Metamaterial is named so as it exhibits properties beyond the properties of naturally available materials. For metamaterials the structural average cell size is smaller than the guided wavelength. It gains its properties from structure rather than composition and is a combination of metal and dielectric composite. The advantage of using Metamaterial structures in patch antennas is that enhanced antenna properties like gain and efficiency can be obtained as well as size of the antenna can be reduced for convenience. Metamaterials are artificial material which exhibit negative permittivity, permeability and refractive index simultaneously, which is not found in readily available materials. Metamaterials have negative refractive index that is a reversal of Snell's law, hence called as negative index materials. Due to negative refractive index, the group and phase velocities of electromagnetic wave appear in opposite direction such that the direction of propagation is reversed with respect to the energy flow direction. Negative μ_r and ε_r occur in nature, but not simultaneously. Negative refraction can be achieved when both μ_r and ε_r are negative, as described in the following equation.

$$
\begin{aligned}
n &= \sqrt{(-\varepsilon_r)(-\mu_r)} \\
&= \sqrt{\varepsilon_r(e^{-j\pi})\mu_r(e^{-j\pi})} \\
&= \sqrt{\varepsilon_r\mu_r}(e^{-j\pi})^{1/2}(e^{-j\pi})^{1/2} \\
&= \sqrt{\varepsilon_r\mu_r}(e^{-j\pi/2}e^{-j\pi/2}) \\
&= -1\sqrt{\varepsilon_r\mu_r} < 0.........(i)
\end{aligned}
$$

Early Metamaterials relied on a combination of Split-ring resonators (SSRs) [10] and conducting wires/posts. SSRs used to generate desired μr for a resonant band of frequencies. Conducting posts are polarized by the electric field, generating the desired εr for all frequencies below a certain cut-off frequency. The SRR based LH Metamaterials only exhibit LH properties around the resonance of the SRR. Therefore realiazation of LH Metamaterials using SRRs are known as the resonant approach. In terms of microwave engineering applications, the resonant approach towards LH Metamaterial is not practical for the following reasons

•Bulky, not applicable to planar microwave circuits

•Narrow-band due to requirement of operation near SRR resonance

•Lossy due to requirement of operation near SRR resonance

To overcome the drawbacks of SRR based LH Metamaterials for microwave engineering the unit cell antenna having via and gaps are used.

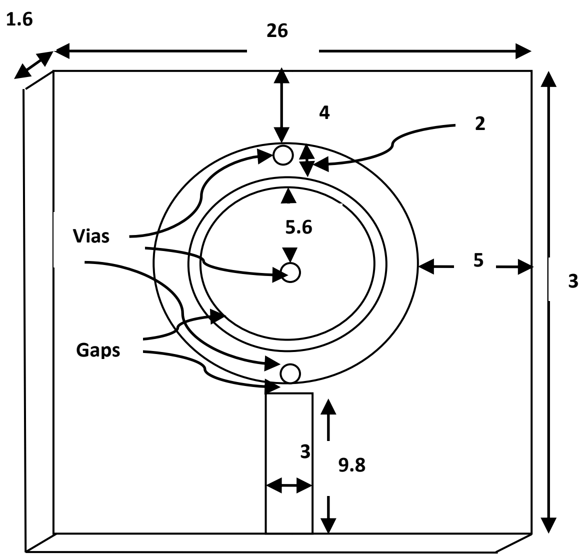
5.2.2 DESIGN OF THE DNG ANTENNA

Here we have designed a single layer planar DNG antenna photo etched on thin substrate [2]. First we have taken a ground plane of 0.5mm next a rectangular substrate (26mm×30mm×1.6mm) of duroid having permittivity 2.2 is developed. A circular patch having radius 8mm, thickness 0.1mm and a gap circle having outer radius 6mm and inner radius 5.8mm is printed on the substrate. As shown in the figure at the centre point of the patch and at the top and bottom of the gap circle there are three vias of radius 0.2mm each. For feeding we have used a microstripline of length 9.8mm, width 3mm and thickness 0.1mm, by using the above dimensions a gap of 0.2 mm is found between the microstrip line and the patch. Our antenna is simulated using CST Microwave Studio [25] based on finite integration method. But as CST transient solver doesn't support negative permittivity and permeability we can't enter negative permittivity and permeability values for the Metamaterial directly, so we have used shunt inductor i.e. via, shunt capacitor i.e. free plate and series capacitor i.e. gap between free plates [15]. Directly, negative permittivity and permeability values can be entered using HFSS, based on finite element method.

5.2.3 RESULTS AND DISCUSSION

For simulation of our antenna we have taken the frequency range 2-5.5 GHz to satisfy the wireless requirements [24]. From the 3D radiation pattern shown in fig 5.9, at 2.4 GHz frequency the gain and efficiency are 4.183 dB and 60.78% respectively and as shown in fig. 5.10 the gain is 5.197 dB, total efficiency is 92.5%. Figure 5.13 shows the VSWR of 1.5 and 1.6 at 2.4 GHz and 5 GHz respectively. These parameters are enough for point to point wireless communication [23]. Figure 5.14 and 5.15 shows a well-balanced surface current for our antenna having a maximum of 48.6 at 2.4 GHz and 43.8 A/m at 5 GHz frequency. Figure 5.11 and 5.12 show the 2D radiation patterns for our antenna with E and H field.

The experimental verification of fabricated patch could not be carried out due to unavailability of high range of network analyser in our lab.



Via Radius=Patch Gap=0.2
All Dimensions in mm
Fig 5.7: Structure of the Antenna

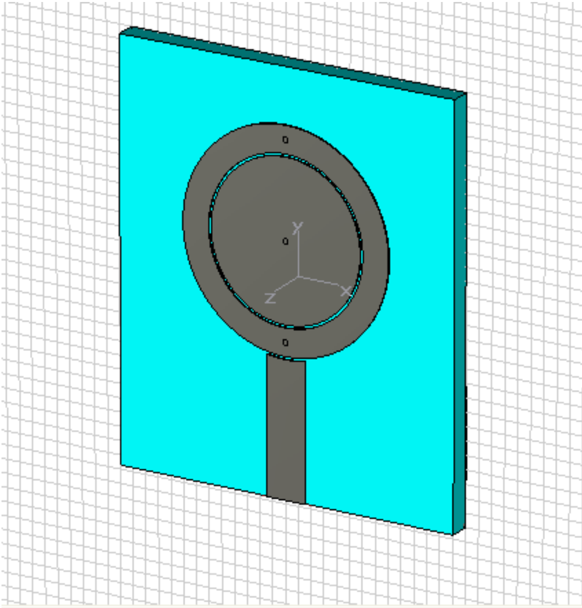


Fig 5.8: Prospective View of the Antenna

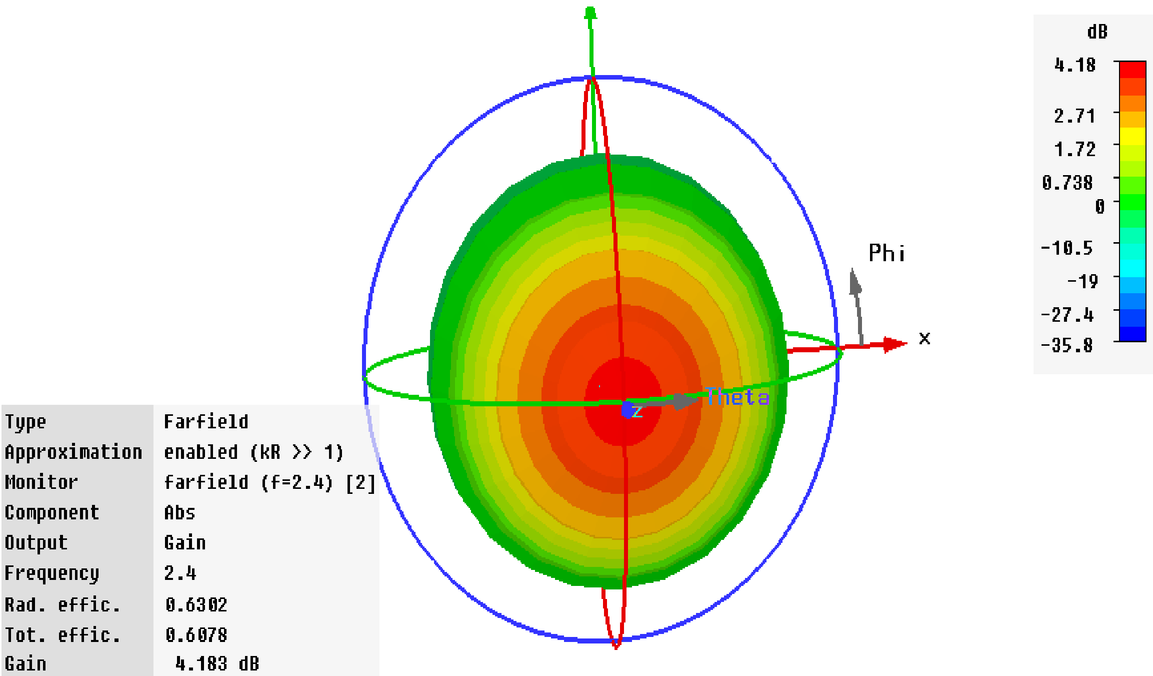


Fig 5.9:3D Radiation Pattern at 2.4 GHz

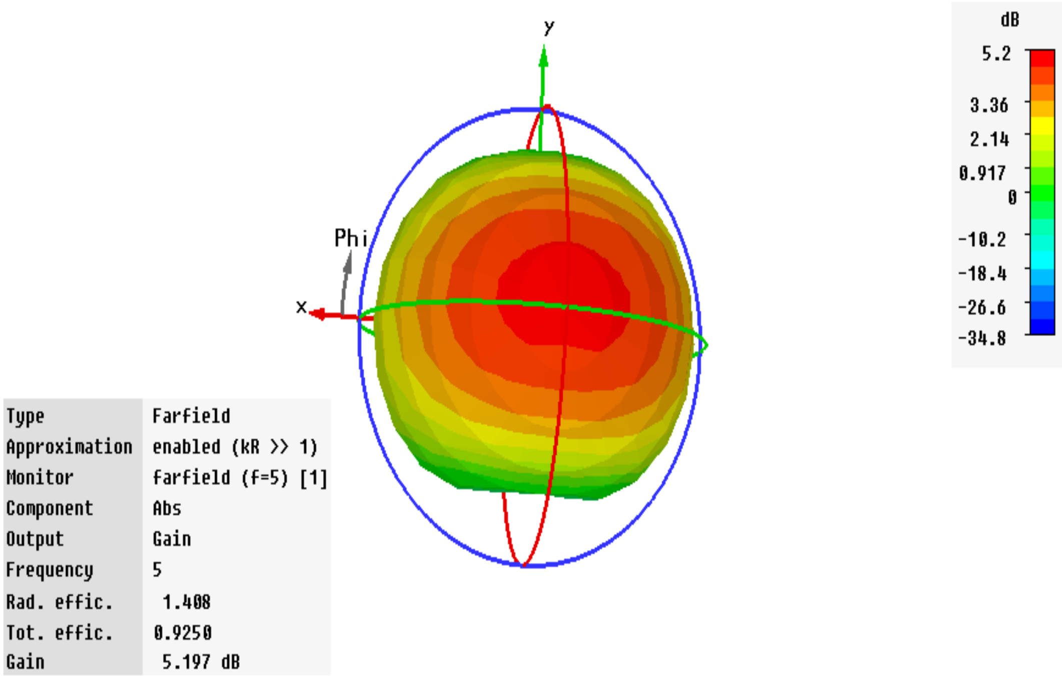


Fig 5.10: 3D Radiation Pattern at 5

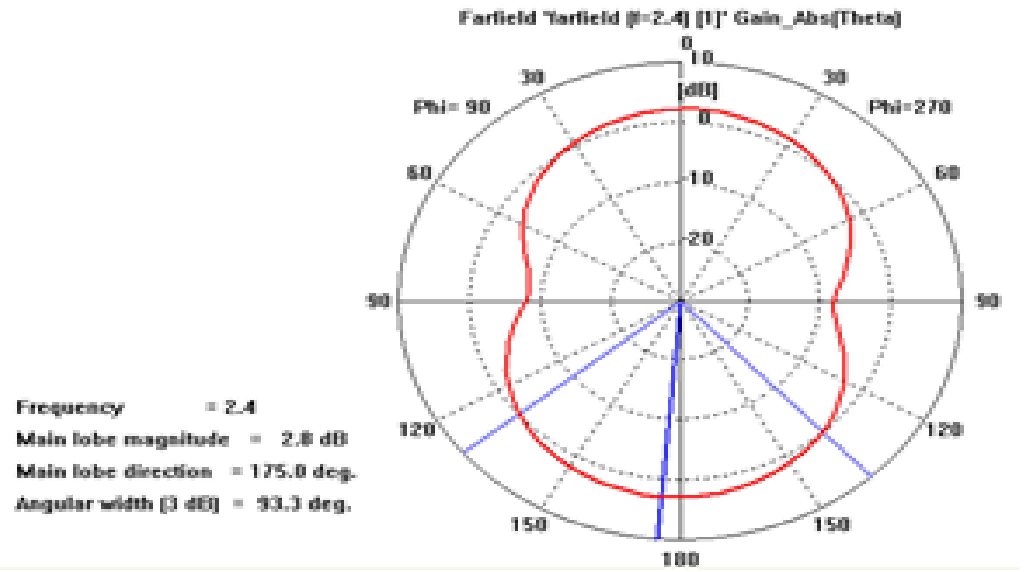


Fig 5.11: 2D Radiation Pattern at 2.4 GHz

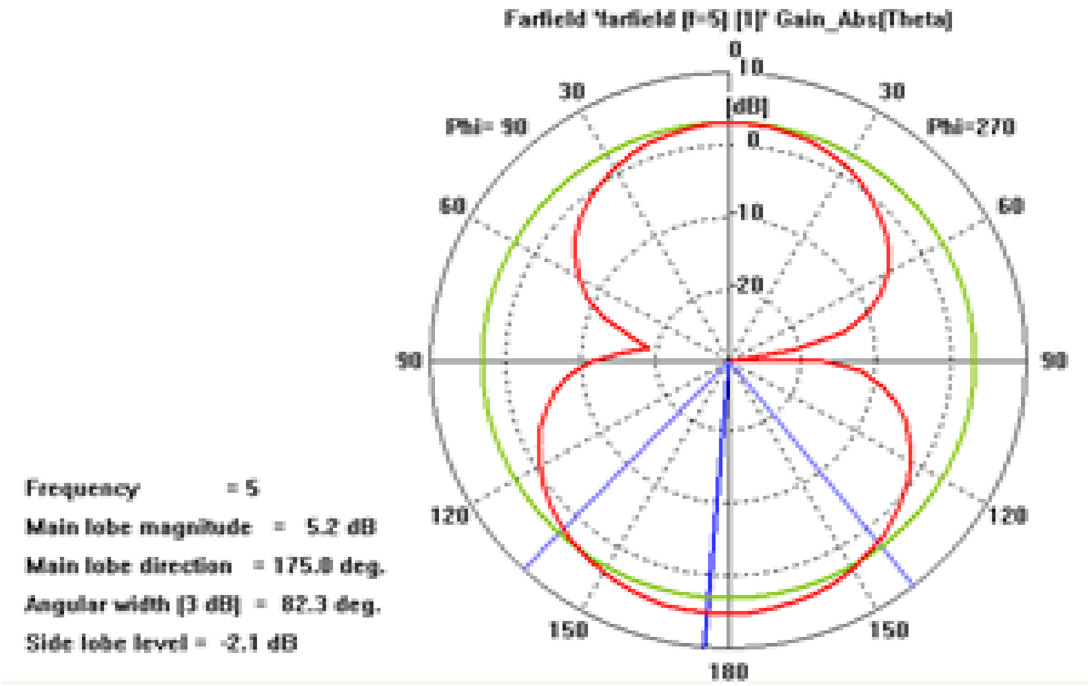


Fig 5.12: 2D Radiation Pattern at 5 GHz

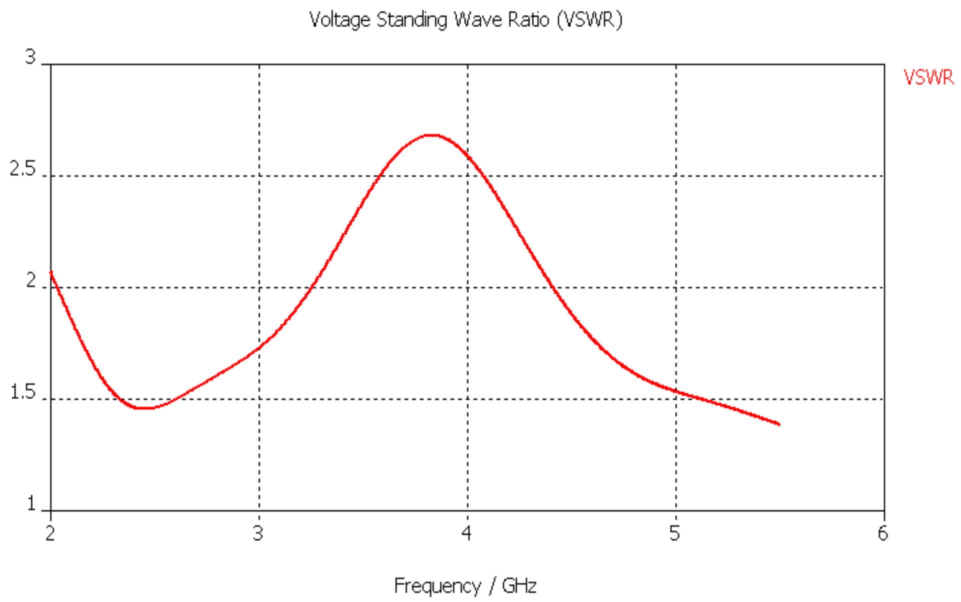


Fig 5.13: VSWR Curve

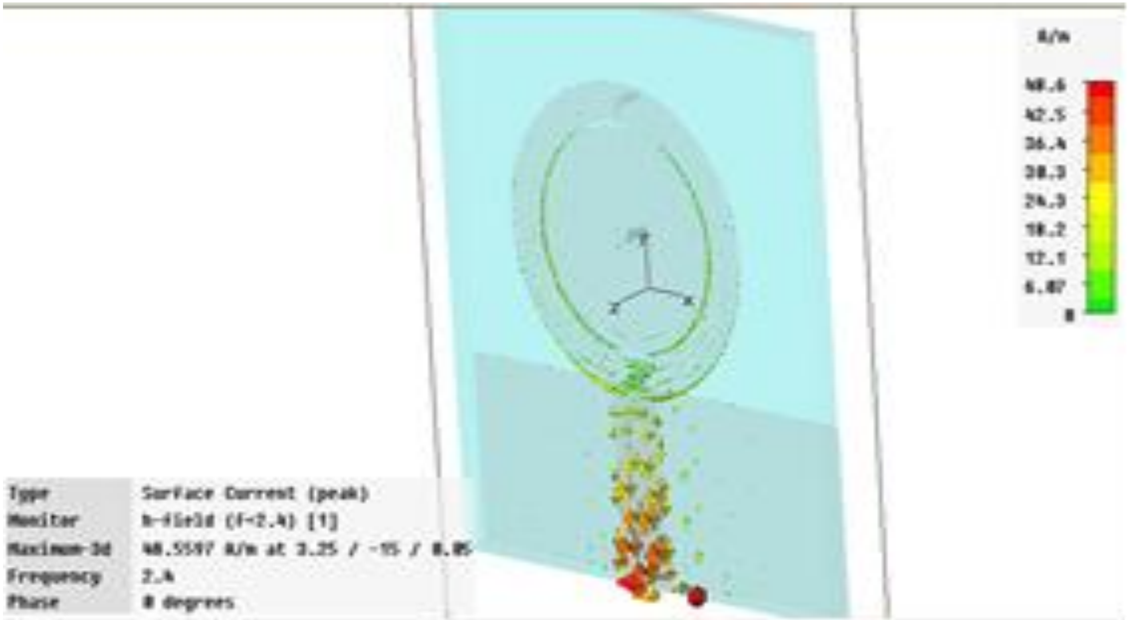


Fig 5.14: Surface currents at 2.4 GHz

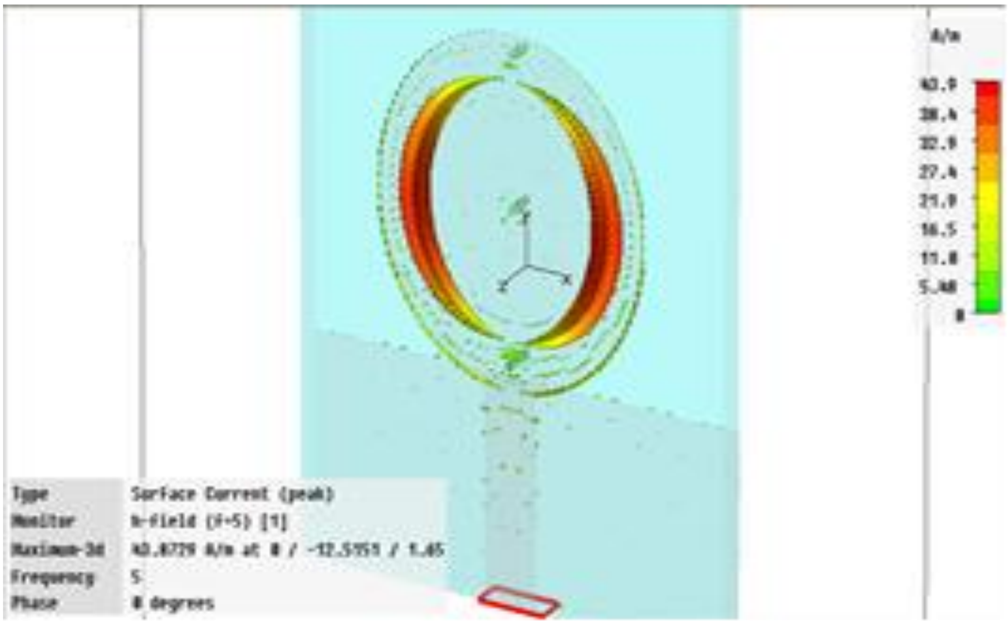


Fig 5.15: Surface currents at 5 GHz

Fig. 5.16: Prototype of Fabricated Antenna

5.2.4 COMPARISON TABLE BETWEEN THE ANTENNAS DISCUSSED

Antenna	Gain in dB	Efficiency in %	VSWR
Single Unit Cell at 5 GHz	3.786	53.76	1.6
Three Unit Cell at 5 GHz	5.197	92.5	1.6
Three Unit Cell at 2.4 GHz	4.183	62.78	1.5

CHAPTER 6

CONCLUSION, PUBLICATION, REFERENCE AND FUTUREWORK

6.1 CONCLUSION

By observing the simulated results it is very clear that the compact DNG Metamaterial antenna gives better gain and efficiency compared to an ordinary patch antenna which is very useful for point to point wireless propagation. This is possible only because of the unusual properties of Metamaterials. Also due to the miniaturization it is very convenient to use in wireless networks. This is possible only because of the unusual properties of Metamaterials. Due to the unusual properties of the Metamaterials by using a single unit cell the antenna gives of 3.768 dB, overall efficiency of 53.76 and a VSWR of 1.6 at 5 GHz frequency which is very good for point to point wireless communication and wireless LANs. This antenna has better VSWR, gain and radiation efficiency compared to an ordinary patch antenna. And another Metamaterial antenna using three unit cells gives a better gain of 5.197 dB, overall efficiency of 92.5% and a VSWR of 1.5 at 2.4 GHz and 1.6 at 5 GHz frequency. And the gain, efficiency and return loss are 4.183 dB, 60.78%, -14.5 respectively for 2.4 GHz. The results obtained through “CST MICROWAVE STUDIO” design software and are very good for wirelessly access network resources at home and elsewhere with up to 5 GHz performance, like IEEE 802.11a, widely available IEEE 802.11b, downwardly compatible IEEE 802.11g, and advanced IEEE 802.11n.

6.2 PUBLICATIONS

[1] Jyotisankar Kalia and S K Behera, “Compact High Radiation Metamaterial Antenna for Wireless Applications” **International Conference on Electronic Systems (ICES-2011),7-9 January 2011 at NIT Rourkela.**

[2] Jyotisankar Kalia, S K Behera and R K Mishra, “Metamaterial Unit Cell Antenna for WLAN Application**” National Conference on Signal Processing, Communications and VLSI (NCSSV-11), 6-7 May 2011 at Anna University of Technology, Coimbatore**

6.3 FUTURE SCOPE OF WORK

[1] Metamaterial unit cells can be formed in the form of Sierpinski Gasket and can be implemented in fractal antennas for frequency independent applications.

[2] Experimental verification of the fabricated patch will be carried out in future.

[3] Design of Metamaterial Antenna for Ultra Wide Band Applications.

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